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(54) A DIRECTLY COOLABLE MULTIFILAMENT CONDUCTOR MEANS

DIREKT KÜHLBARE MULTIFILAMENTLEITERMITTEL

MOYEN CONDUCTEUR MULTIFILAMENTS REFROIDISSABLE DIRECTEMENT

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Description

[0001] The invention relates to a directly coolable multifilament conductor means for a magnetic coil, comprising at least two electric conductors and at least one cooling tube disposed between the conductors adapted to carry a fluid cooling means.

[0002] A directly coolable multifilament conductor means as depicted above is for example used for building a magnetic coil in form of or being part of a gradient coil of a magnetic resonance apparatus. In order to assure operation of a magnetic coil it is necessary to maintain the temperature of the coil below a maximally allowed temperature. It is necessary to efficiently eliminate the electrical dissipated power that arises in the form of heat produced when operating the magnetic coil. Since in many applications, for example when operating a gradient coil, a dissipated power in the order of more than 20 KW can be involved, considerable demands are made on the cooling system.

[0003] A magnetic coil comprising a directly coolable multifilament conductor means is disclosed in US 6 741 152 B1. The conductor means comprises at least two profiled electrical conductor segments which when fitted together form an opening with a cooling tube being enclosed in this opening between the segmented conductors, with the cooling tube being adapted to carry a fluid cooling means for directly cooling the conductors and for transporting the dissipated heat. The tube is made of a non-conductive flexible plastic or polymer material, which material also encloses the segmented conductors being disposed at the sides of the rectangular inner tube. The polymer or plastic tube is fluid tight, leakage problems can be avoided. Such a multifilament conductor means is advantageous compared to a monolithic hollow conductor, which allows for a direct cooling of the conductor but which is subjected to eddy currents, which are one of the natural sources for the heating of the conductor, especially when high frequencies are used as for example at the magnetic resonance imaging. A directly coolable multifilament conductor means as for example disclosed in US 6 741 152 B1 is less sensitive to eddy currents, which may not only lead to heating the conductor but may also create non-compensatable magnetic eddy current fields which are negative for example for the imaging procedure.

[0004] The integrated tube allows for a good cooling of the conductor. As the tube needs to have a certain cross section to have the necessary flow rate of the cooling fluid flowing through the conductor, the effective conductor cross section, which is determined by the conductive filaments arranged at the sides of the cooling tube, is quite small, compared to the overall cross section of the whole conductor means.

[0005] Further prior art examples of directly coolable multifilament inductor means are known from CA1210464A, CN106910553A, CA1241703A1, US3737989A1 and US2018/120394A1.

[0006] It is an object of the invention to provide an improved directly coolable multifilament conductor means for a magnetic coil having good electric properties with a low sensitivity to eddy currents as well as a good cooling property.

[0007] The object is inventively achieved with a directly coolable multifilament conductor means as defined in claim 1.

[0008] According to the invention the tube adapted to carry a fluid cooling means also acts as a filament adapted to carry the current when the magnetic coil is in operation. It therefore has a double function. This is achieved by providing a cooling tube made of metal, so that the cooling tube can act as a conductor. The tube is therefore also a filament, which allows for minimizing the eddy currents in the conductor means and provides a good cooling of the conductor means due to the small thermal resistance between the cooling means and the heat sources, i.e. the conductors. As the tube is made of metal it also participates in carrying the current. But as the cooling tube is made of metal having a lower conductivity than the material the surrounding conductors are made of, the tube shows a lower sensitivity to eddy currents. It is therefore possible to integrate a cooling tube having a sufficient cross section for allowing a sufficient fluid rate to be transported through the tube. Due to the low sensitivity to eddy currents of the tube material the tube may therefore have a larger effective eddy current surface, compared to the filament conductors, but does not dominate or significantly negatively influence the electrical properties in view of eddy currents.

[0009] So the inventive multifilament conductor means provides a very good cooling efficiency and very good electrical properties with a reduction of unwanted eddy current effects.

[0010] The tube is preferably made of steel, especially stainless steel, while the conductors are made of copper or aluminium. Steel, especially stainless steel, shows very good properties regarding its electrical conductivity and the thermo conductivity, but also the mechanical properties. It also shows a very low tendency to erosion and a very tendency to transmit ions into the liquid cooling means. Another advantage is the possibility to produce a hollow filament conductor with a very thin wall thickness. Due to the lower electrical conductivity of the tube material it is advantageous to use a tube with a very small material cross section to avoid that the effective conductor cross section of the overall conductor becomes too large and to avoid rising of the thermal resistance. As the hollow tube has a significantly larger diameter or cross section compared to the monolithic conductor filament the lower conductivity of the steel will lead to a significant reduction of the negative eddy current effects.

[0011] The metal respectively the steel the tube is made of preferably shows no or negligible magnetic properties, even if it is deformed when the conductor means is bent, as the conductor means usually is when the magnetic coil, especially a gradient coil is produced, in order to avoid any inhomogeneities of the overall created magnetic field.

[0012] The tube has preferably a wall thickness between 0.5 - 1.5 mm, while the thickness is preferably as low as possible as explained above.

[0013] Furthermore, the tube may either have a rectangular cross section or a circular cross section, with the conductors being arranged only locally at the sides of the tube or surrounding the rectangular or circular tube.

[0014] In case the tube has a rectangular cross section it preferably has a width between 2 - 10 mm, especially between 3 - 7 mm, and a height between 2 - 10 mm, especially between 3 - 7 mm. The hollow cross section can vary depending on various parameters in order to ascertain that the necessary flow rate of the liquid cooling means can flow through the tube while also avoiding that the tube cross section is too large for the intended application, so that the overall cross section of the conductor means can vary in a larger range with optimized cooling properties.

[0015] The same is true for a circular tube, which also preferably has an outer diameter between 2 - 10 mm, especially between 3 - 7 mm.

[0016] The conductors have a rectangular cross section. They preferably have a width between 1 - 8 mm, especially between 1 - 5 mm, and a height between 2 - 10 mm, especially between 3 - 7 mm. Depending on the number of rectangular conductors, which are preferably used in combination with a rectangular tube, the conductor dimensions are chosen. It is possible to arrange several stacked conductors adjacent to the side of the tube, which conductors have a smaller width and height compared to the tube. But it is also possible to use at least one conductor at opposing sides of the rectangular tube having the same height as the tube etc. There are several different layouts possible.

[0017] The conductors themselves may comprise an isolating surface coating, for example a varnish or a polymer coating. This coating is especially used when the conductors are made of copper. In case they are made of aluminium such a coating is only optional, as the aluminium usually has a passivation layer on its surface which acts as an isolating layer.

[0018] Finally, the conductors and the tube may also be embedded in a flexible casting or a flexible coating. According to this embodiment, the whole conductor means is casted or coated in a flexible material, preferably a polymer or plastic material which is flexible enough to allow the conductor means to be bent. It may also show elastic properties for allowing the elastic material to be stretched and compensated at bends with a smaller radius.

[0019] The invention also refers to a directly cooled magnetic coil comprising at least one conductor means as depicted above forming a coil winding. The coil itself is preferably a gradient coil for a magnetic resonance apparatus.

[0020] Finally, the invention refers to a magnetic resonance apparatus comprising at least one coil as depicted above.

[0021] Further advantages of the invention are explained below in combination with various embodiments shown in the figures. The figures show:

Fig. 1: A principle sketch of an inventive magnetic resonance apparatus comprising an inventive gradient coil, and

Figs. 2 - 10: Various principle sketches of different conductor means comprising a metal tube adapted to carry a liquid cooling means and several conductors having a higher conductivity than the metal tube, which conductors are arranged around the tube.

[0022] Fig. 1 shows a principle sketch of an inventive magnetic resonance apparatus comprising a housing 2 with a central bore 3 into which an object, for example a patient, to be imaged is arranged.

[0023] In the housing 2 among others a gradient coil 4 is arranged comprising several magnetic coils 5, which are usually embedded in a hardened grouting material, usually a polymer. Each coil is made of an inventive conductor means 6 being wound into a respective geometry needed for creating the respective magnetic field. The setup and the properties of such a gradient coil 4 are known.

[0024] Fig. 2 shows a first embodiment of an inventive conductor means 6. The conductor means is a directly coolable multifilament conductor means. It comprises a cooling tube 7 arranged in the center of the conductor means 6. The cooling tube 7 is adapted to carry a fluid cooling means through a central channel 10 which is issued to cool the conductor means 6 which gets heated under operations due to the current being carried by the conductor means 6 and due to eddy currents. The tube 7 is made of metal, preferably steel, especially stainless steel. It has a rectangular cross section, with the wall thickness being between 0.5 - 1 mm. The width of the tube 7, seen in the horizontal direction, is clearly smaller than its height. The width may for example be between 2 - 4 mm, while the height is between 6 - 10 mm.

[0025] At the two opposing long sides of the tube 7 several conductors 8 also having a rectangular shape are arranged in a stacked manner. Each stack comprises for example four conductors 8. The conductors having a higher electrical conductivity than the metal tube are made of copper or aluminium. In case they are made of copper they preferably comprise an isolating surface coating 9, preferably a varnish or a polymer coating. In case they are made of aluminium such a coating is optional due to the passivation layer usually present on an aluminium surface.

[0026] The rectangular conductors, which may also have a square cross section, for example have a width between 2 - 4 mm and a height between 2 - 4 mm, while also these geometry parameters are only exemplary.

[0027] The conductors 8 are stacked above and adjacent to each other, but are not fixed to each other. They are also not fixed to the tube 7. This allows a certain movement of the respective components relative to each other, so that the conductor means 6 can be bent and wound into a coil form.

[0028] The heat produced in operation of the conductor means respectively the coil is transported to the metal tube 7 having a low thermal resistance, so that the heat can be transferred to the cooling means flowing through the hollow tube 7. This allows for a very effective cooling of the cooling means 6. Aside that the metal tube 7 also acts as a filament carrying the operational current. As it has a lower conductivity compared to the electric conductivity of the copper or aluminium conductors it is possible, especially when the wall thickness of the tube 7 is small, that the tube 7 has an efficiently large hollow cross section, so that the necessary flow rate of cooling fluid through the tube 7 can be realized.

[0029] Fig. 3 shows another embodiment of an inventive conductor means 6, with the same reference numbers being used for the same components. Also, this conductor means comprises a hollow rectangular tube 7 being made of a metal having a lower electrical conductivity than the conductors 8 being arranged around all four sides of the rectangular tube 7. The conductors 8 are made of copper or aluminium with an optional isolating surface coating 9, for example a varnish or a polymer coating.

[0030] Fig. 4 shows an embodiment of an inventive conductor means 6 which is comparable to the embodiment of fig. 3. Different to fig. 3 the hollow tube 7 of fig. 4 has a circular or oval cross section. The conductors 8 are arranged around the tube 7, comparable to the embodiment of fig. 3.

[0031] Fig. 5 shows an embodiment of a cooling means 6 with a rectangular metal tube 7 and several conductors 8 also having a rectangular shape with a width and height comparable to the dimensions of the tube 7. In this embodiment at each long side of the tube 7 three conductors 8 are arranged, each comprising an optional isolating surface coating 9. Also, this embodiment allows a very good heat transfer to the cooling means flowing through the metal tube 7, which itself acts as a filament conductor.

[0032] Fig. 6 shows an embodiment comparable to fig. 5. It comprises a hollow tube 7 made of metal having a lower conductivity than the metal conductors 8. The tube 7 and the conductors 8 are arranged in a horizontal direction, with three conductors 8 being stacked above each other and arranged at each side of the tube 7. Also here the geometry of each conductor 7 is comparable to the tube geometry.

[0033] Fig. 7 shows a conductor means 6, with a hollow tube 7 with a vertical orientation and with respective conductors 8 having a horizontal orientation, which are arranged at both long sides of the tube 7. In this embodiment at each side five conductors 8 are arranged. The conductor 8 in the middle of each conductor stack is thicker than the other conductors being arranged below and above the center conductor. By changing the cross section the electrical properties, especially the effective conductor cross section, may be varied and adjusted.

[0034] Fig. 8 shows an example which is outside the scope of the appended claims of a conductor means 6 with a circular tube 7 being arranged in the center of the circular arrangement. Through its central channel 10 the liquid cooling means flows for transporting the heat away from the conductor means 6. The circular tube has an outer diameter between 2 - 10 mm, especially between 3 - 7 mm and is made of a metal having a lower electrical conductivity compared to the electrical conductivity of the conductors 8 arranged around the circular tube 7. The conductors 8 also have a circular cross section with a diameter also chosen between 2 - 10 mm, especially between 3 - 7 mm, but with a preferably smaller diameter compared to the diameter of the tube 7. The conductors 8 may also comprise an isolating surface layer 9, especially when they are made of copper. The conductors 8 may be twisted around the central tube 7.

[0035] Fig. 9 shows an example which is outside the scope of the appended claims of a conductor means 6 which also comprises a hollow circular tube 7 around which the circular conductors 8 are arranged. In this example the whole setup is casted into a flexible casting 11 made of a polymer or plastic material, which preferably also has elastic properties. The casting 11 fixes the conductors 8 relative to the tube 7, with the conductors still being in a thermal connection to the tube 7. Due to its flexibility and elasticity it is possible to bend the conductor means 6, while the flexibility and elasticity allow for stretching and compressing at the respective bends and also allows for a certain movement of the conductors 8 in the bending region.

[0036] The conductors 8 may have an isolating surface coating 9, but this coating especially in this case is optional.

[0037] Finally, fig. 10 shows a conductor means 6 comprising a circular hollow tube 7 and circular conductors 8 being arranged around the tube 7. Again, the conductors are made of a metal having a higher electrical conductivity than the metal tube 7. The conductors 8 may have an optional isolating surface layer 9.

[0038] In this example which is outside the scope of the appended claims a flexible or elastic coating 12 is arranged around the conductors 8 encasing the whole conductor means.

[0039] Although the casting 11 or the coating 12 are shown only at the embodiments of figs. 9 and 10 with the circular tube 7 and the circular conductors 8, it is to be noted that also the other embodiments shown in figs. 2 to 7 may certainly be embedded in a casting 11 or in a coating 12 if need be.

[0040] Although the present invention has been described in detail with reference to the preferred embodiment, the present invention is not limited by the disclosed examples from which the skilled person is able to derive other variations but only by the appended claims.

Claims

1. A directly coolable multifilament conductor means (6) adapted for a magnetic gradient coil of a magnetic resonance apparatus, comprising at least two electric conductors (8) and at least one cooling tube (7) disposed between the conductors (8) adapted to carry a fluid cooling means, whereby the tube (7) has a rectangular or a circular cross section and the conductors (8) have a rectangular cross section, **characterized in that** the cooling tube (7) is a metal conductor having a lower electrical conductivity than the conductors (8) surrounding the tube (7).

2. Conductor means according to claim 1, **characterised in that** the tube (7) is made of steel, especially stainless steel and that the conductors (8) are made of copper or aluminium.

3. Conductor means according to claim 1 or 2, **characterised in that** the tube (7) has wall thickness of 0,5 - 1,5 mm.

4. Conductor means according to one of the preceding claims, **characterised in that** the rectangular tube (7) has a width between 2 - 10 mm, especially between 3 - 7 mm and a height between 2 - 10 mm, especially between 3 - 7 mm and that the circular tube (7) has a diameter between 2 - 10 mm, especially between 3 - 7 mm.

5. Conductor means according to one of the preceding claims, **characterised in that** the rectangular conductors (8) have a width between 1 - 8 mm, especially between 1 - 5 mm and a height between 2 - 10 mm, especially 3 - 7 mm.

6. Conductor means according to one of the preceding claims, **characterised in that** the conductors (8) are twisted around the tube (7).

7. Conductor means according to one of the preceding claims, **characterised in that** the conductors (8) comprise an isolating surface coating (9).

8. Conductor means according to claim 7, **characterised in that** the coating (9) is a varnish or a polymer coating.

9. Conductor means according to one of the preceding claims, **characterised in that** the conductors (8) and the tube are embedded in a flexible casting (11) or a flexible coating (12).

10. A directly cooled magnetic coil comprising at least one conductor means (6) according to one of the preceding claims forming a coil winding.

11. Coil according to claim 10, **characterised in that** the coil is a gradient coil (4) for a magnetic resonance apparatus (1).

12. Magnetic resonance apparatus, comprising at least one coil (4) according to claim 10 or 11.

Patentansprüche

1. Direkt kühlbare Multifilamentleitervorrichtung (6), die für eine Magnetgradientspule eines Magnetresonanzapparats vorgesehen ist, umfassend mindestens zwei elektrische Leiter (8) und mindestens einen Kühlkanal (7), der zwischen den Leitern (8) angeordnet ist und dazu ausgebildet ist, ein Fluidkühlmittel zu transportieren, wobei der Kühlkanal (7) einen rechteckigen oder kreisförmigen Querschnitt aufweist und die Leiter (8) einen recheckigen Querschnitt aufweisen, **dadurch gekennzeichnet, dass** der Kühlkanal (7) ein Metallleiter mit einer niedrigeren elektrischen Leitfähigkeit ist als die Leiter (8), welche den Kühlkanal (7) umgeben.

2. Multifilamentleitervorrichtung nach Anspruch 1, **dadurch gekennzeichnet, dass** der Kühlkanal (7) aus Stahl gefertigt ist, insbesondere aus rostfreiem Stahl, und dass die Leiter (8) aus Kupfer oder Aluminium gefertigt sind.

3. Multifilamentleitervorrichtung nach Anspruch 1 oder 2, **dadurch gekennzeichnet, dass** der Kühlkanal (7) eine Wanddicke von 0,5 bis 1,5 mm aufweist.

4. Multifilamentleitervorrichtung nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** der rechteckige Kühlkanal (7) eine Breite zwischen 2 und 10 mm, insbesondere zwischen 3 und 7 mm, und eine Höhe zwischen 2 und 10 mm, insbesondere zwischen 3 und 7 mm aufweist, und dass der kreisförmige Kühlkanal (7) einen Durchmesser zwischen 2 und 10 mm, insbesondere zwischen 3 und 7 mm aufweist.

5. Multifilamentleitervorrichtung nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** die rechteckigen Leiter (8) eine Breite zwischen 1 und 8 mm, insbesondere zwischen 1 und 5 mm, und eine Höhe zwischen 2 und 10 mm, insbesondere 3 und 7 mm aufweisen.

6. Multifilamentleitervorrichtung nach einem der vor-

hergehenden Ansprüche, **dadurch gekennzeichnet, dass** die Leiter (8) um den Kühlkanal (7) herum verdrillt sind.

7. Multifilamentleitervorrichtung nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** die Leiter (8) eine isolierende Oberflächenbeschichtung (9) umfassen.

8. Multifilamentleitervorrichtung nach Anspruch 7, **dadurch gekennzeichnet, dass** die Beschichtung (9) ein Lack oder eine Polymerbeschichtung ist.

9. Multifilamentleitervorrichtung nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** die Leiter (8) und der Kühlkanal in ein flexibles Gussmaterial (11) oder eine flexible Beschichtung (12) eingebettet sind.

10. Direkt gekühlte Magnetspule, die mindestens eine Multifilamentleitervorrichtung (6) nach einem der vorhergehenden Ansprüche umfasst, das eine Spulenwindung bildet.

11. Spule nach Anspruch 10, **dadurch gekennzeichnet, dass** die Spule eine Gradientenspule (4) für einen Magnetresonanzapparat (1) ist.

12. Magnetresonanzapparat, umfassend mindestens eine Spule (4) nach Anspruch 10 oder 11.

Revendications

1. Moyen (6) conducteur à multi-filaments pouvant être refroidi directement, conçu pour une bobine à gradient magnétique d'une installation de résonance magnétique, comprenant au moins deux conducteurs (8) électriques et au moins un tube (7) de refroidissement disposé entre les conducteurs (8) et conçu pour faire passer un moyen de refroidissement par fluide, le tube (7) ayant une section transversale rectangulaire ou circulaire et les conducteurs (8) ayant une section rectangulaire, **caractérisés en ce que** le tube (7) de refroidissement est un conducteur métallique ayant une conductivité électrique plus petite que les conducteurs (8) entourant le tube (7).

2. Moyen conducteur suivant la revendication 1, **caractérisés en ce que** le tube (7) est en acier, en particulier en acier inoxydable, et **en ce que** les conducteurs (8) sont en cuivre ou en aluminium.

3. Moyen conducteur suivant la revendication 1 ou 2, **caractérisés en ce que** le tube (7) a une épaisseur de paroi de 0,5 à 1,5 mm.

4. Moyen conducteur suivant l'une des revendications précédentes, **caractérisés en ce que** le tube (7) rectangulaire a une largeur comprise entre 2 et 10 mm, en particulier entre 3 et 7 mm et une hauteur comprise entre 2 et 10 mm, en particulier entre 3 et 7 mm et **en ce que** le tube (7) circulaire a un diamètre compris entre 2 et 10 mm, en particulier entre 3 et 7 mm.

5. Moyen conducteur suivant l'une des revendications précédentes, **caractérisés en ce que** les conducteurs (8) rectangulaires ont une largeur comprise entre 1 et 8 mm, en particulier entre 1 et 5 mm, et une hauteur comprise entre 2 et 10 mm, en particulier entre 3 et 7 mm.

6. Moyen conducteur suivant l'une des revendications précédentes, **caractérisés en ce que** les conducteurs (8) sont enroulés autour du tube (7).

7. Moyen conducteur suivant l'une des revendications précédentes, **caractérisés en ce que** les conducteurs (8) comprennent un revêtement (9) de surface isolant.

8. Moyen conducteur suivant la revendication 7, **caractérisé en ce que** le revêtement (9) est un vernis ou un revêtement polymère.

9. Moyen conducteur suivant l'une des revendications précédentes, **caractérisés en ce que** les conducteurs (8) et le tube sont incorporés dans une pièce coulée (11) souple ou dans un revêtement (12) souple.

10. Bobine magnétique refroidie directement et comprenant au moins un moyen (6) conducteur suivant l'une des revendications précédentes formant un enroulement de bobine.

11. Bobine suivant la revendication 10, **caractérisée en ce que** la bobine est une bobine (4) à gradient pour une installation (1) de résonance magnétique.

12. Installation de résonance magnétique, comprenant au moins une bobine (4) suivant la revendication 10 ou 11.

FIG 1

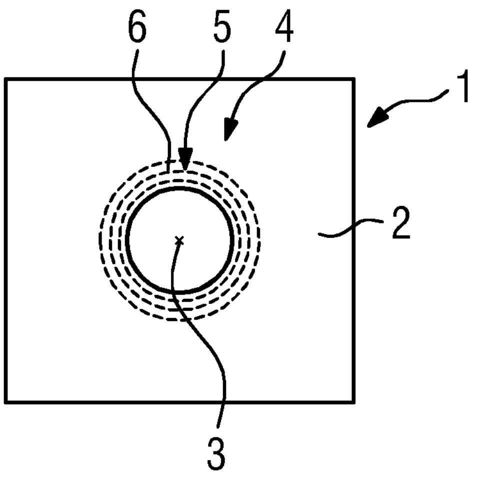


FIG 2

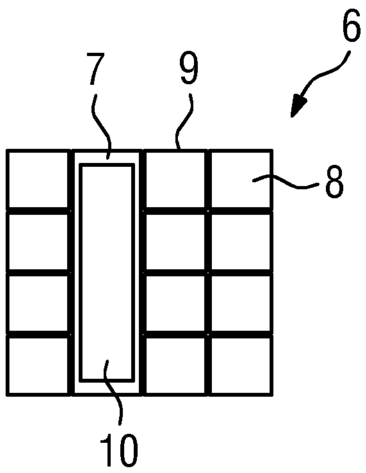


FIG 3

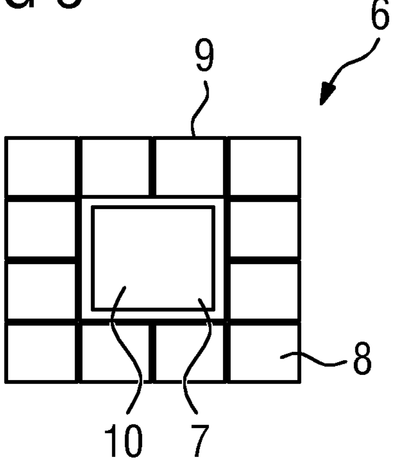


FIG 4

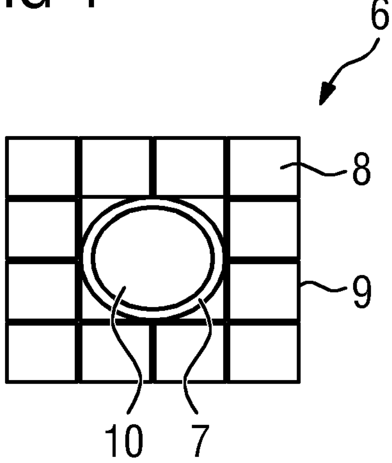


FIG 5

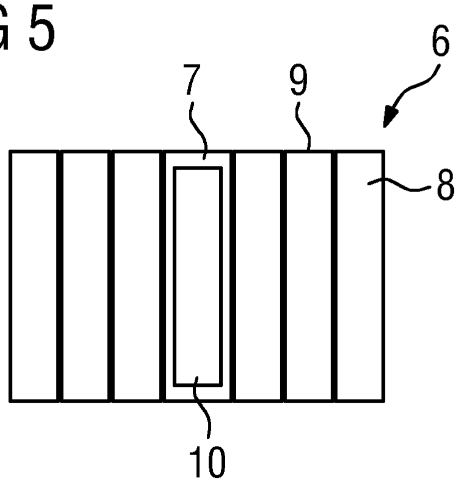


FIG 6

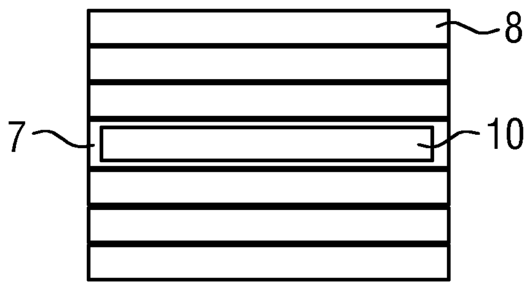


FIG 7

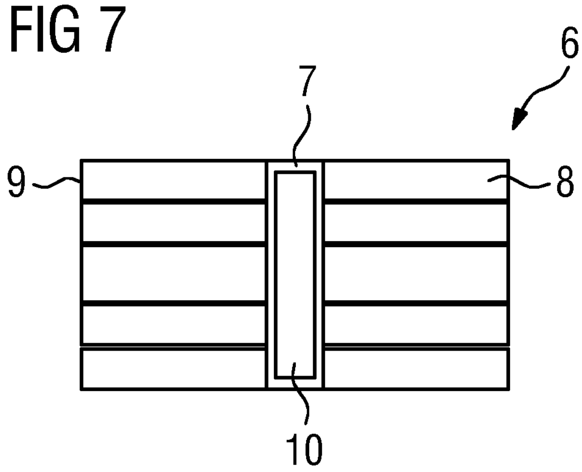


FIG 8

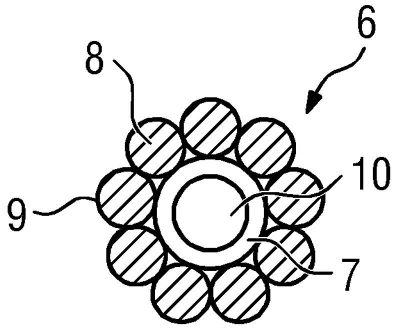


FIG 9

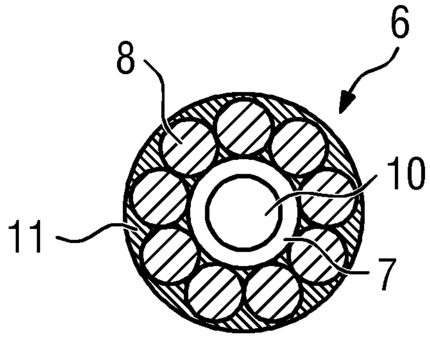
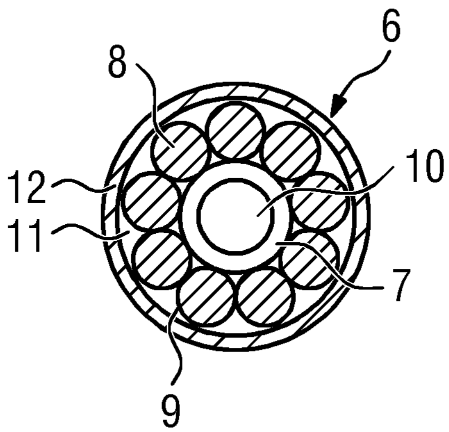


FIG 10



REFERENCES CITED IN THE DESCRIPTION

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